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TITLE: PRELIMINARY DESCRIPTION OF THE GROUND TEST ACCELERATOR CRYOGENIC COOLING SYSTEM

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PRELIMINARY DESCRIPTION OF THE GROUND TEST ACCELERATOR CRYOGENIC COOLING SYSTEM

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I. INTRODUCTION

The Ground Test Accelerator (GTA) under construction at the Los Alamos National Laboratory is part of the Neutral Particle Beam Program supported by the Strategic Defense Initiative Office. The GTA is a full-sized test facility to evaluate the feasibility of using a negative ion accelerator to produce a neutral particle beam (NPB). The NPB would ultimately be used outside the earth's atmosphere as a target discriminator or as a directed energy weapon.

The operation of the GTA at cryogenic temperature is advantageous for two reasons: first, the decrease of temperature causes a corresponding decrease in the rf heating of the copper in the various units of the accelerator, and second, at the lower temperature the decrease in the thermal expansion coefficient also provides greater thermal stability and consequently, better operating stability for the accelerator.

The ratio of the electrical resistance of copper at room temperature to that at cryogenic temperature can attain values well in excess of 100. However, this same comparison does not hold for rf heating. The theoretical ratio for rf heating power for copper, given in Figure 1, shows that most of the advantage of cryogenic cooling (maximum ratio of about 5) is attained when the temperature is below 50 K.

A similar comparison of the thermal expansion coefficient shows that the expansion coefficient is 1.8×10^{-5}/K at ambient temperature and has decreased to about 2.8×10^{-6} at 50 K. Although the value of the thermal expansion continues to decrease (becoming another order of magnitude smaller at 20 K) the above reduction was considered sufficient to insure satisfactory operation of the GTA, provided the temperature variation during operation at full power within the individual components is kept to a minimum, say 1 or 2 K.

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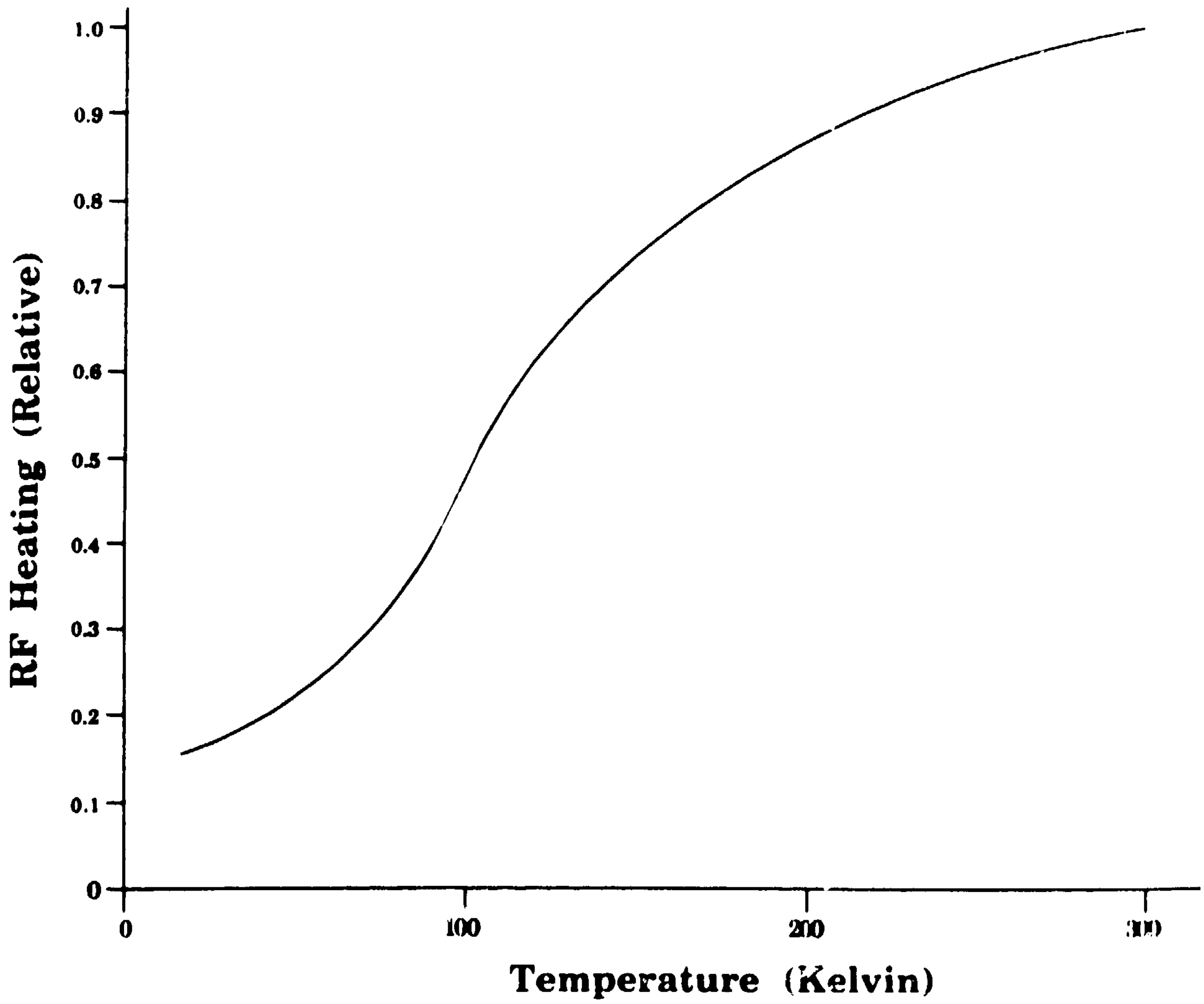

Fig. 1. Relative rf-heating of copper as a function of temperature showing a dramatic reduction in rf heating is obtained at low temperature.

The temperature of the liquid hydrogen (20 K) is close to the lowest that is conveniently available for operation in space. To obtain the maximum benefit of whatever coolant is to be used in the GTA, the temperature of the coolant must be allowed to rise as it passes through the GTA (avoiding two-phase flow). This temperature rise, along with the necessary temperature gradients within the copper being cooled and the temperature difference across the coolant film, all require that the GTA have an operating temperature considerably above 20 K. Thus, the operation of the GTA is planned to be at a maximum temperature of 50 K with the coolant entering at as low a temperature as practical.

II. GTA

The GTA will accelerate negative ions (H^-) to the desired discharge energy (100 MeV) and will consist of several units. First, an injector will produce the H^- ions at an energy of 40 keV for their introduction into a radio frequency quadrupole (RFQ) where they will be accelerated to an energy of 2.5 MeV. The negative ions next travel to a drift tube linear accelerator (DTL) where they are accelerated to an energy of 24 MeV. Finally, a combination of DTL plus a side coupled cavity accelerator (CCL) will complete the acceleration to 100 MeV, after which the extra electron will be stripped from the H^- ion by passage through a thin metal foil to produce a beam of neutral hydrogen atoms. Figure 2 is a block diagram showing the various units of the complete accelerator, and indicating which units are to be cooled to cryogenic temperature (less than 50 K). A pictorial representation of the GTA is presented in Figure 3 .

The heat load to the various units of the GTA will consist of rf heating in the copper of the accelerator units (the largest load), thermal heat leak from the environment, and beam spill (impingement of the beam particles at the outer edges of the beam upon the accelerator structure). The beam steering magnet will also contribute resistive heating losses. External to the accelerator, other heat loads will be contributed by the thermal heat leaks and other energy inputs to the transfer lines and the remainder of the cryogenic system.

The testing of the complete accelerator will proceed in steps with various of its units being first tested individually, then in combination wi

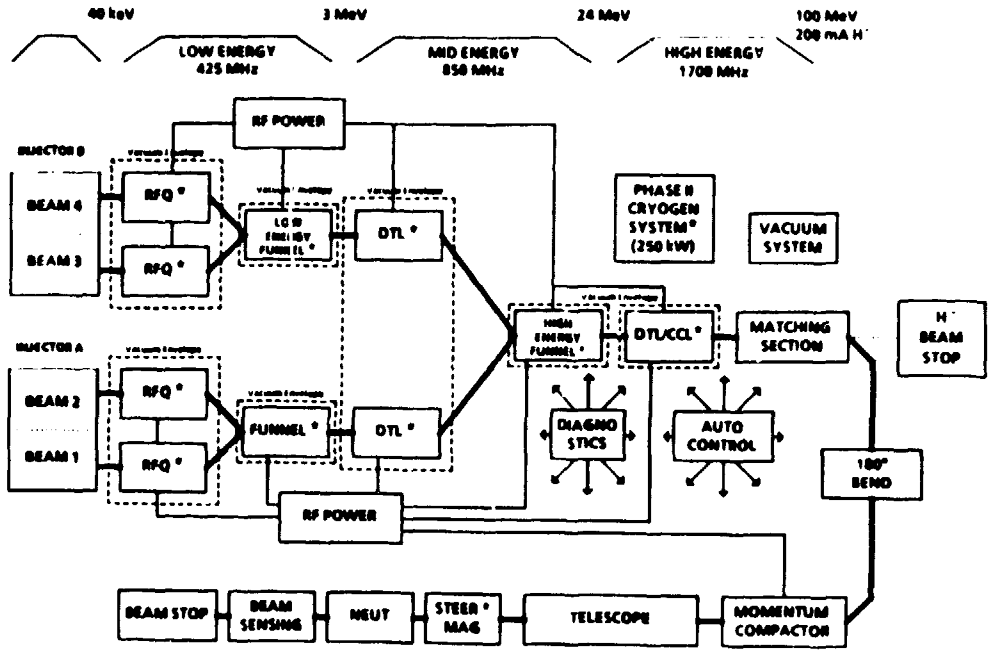

Fig. 2. Block diagram of the full GTA configuration (100 MeV, 200 mA H^-) with cryogenically cooled components indicated by an asterisk(*).

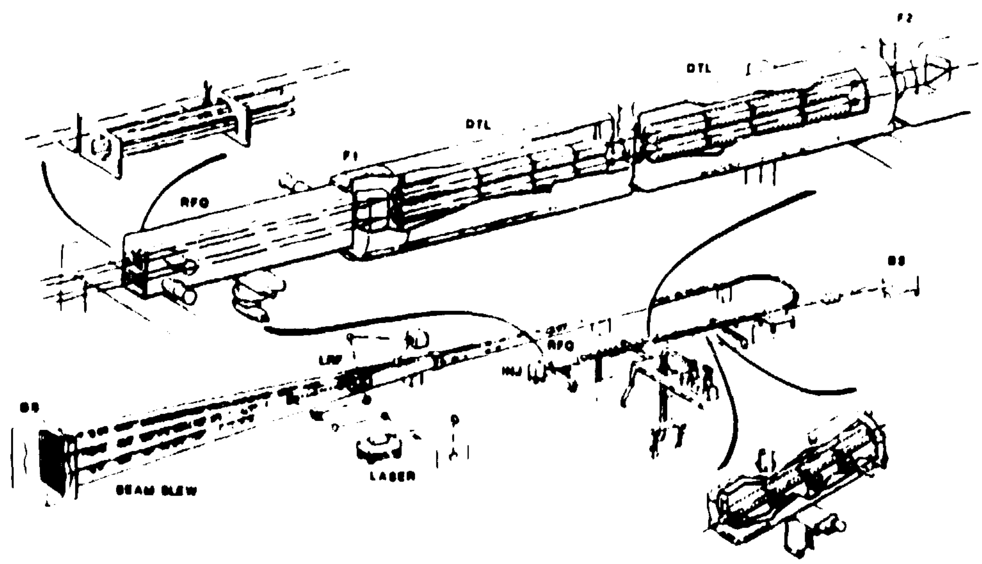

Fig. 3. Pictorial representation of the GTA.

others. Therefore, six experiments are planned before the addition of the final DTL/CCL, which will accommodate the 100 MeV operation. Table I shows the components involved in the various experiments and their cooling loads and masses. Table II shows the numbers of each of the components involved in a particular experiment, the resultant cooling load, and the expected additional thermal loads and external heat leaks for each of the experiments.

For application in space, the obvious choice for a coolant would be the liquid hydrogen that will already be present as a fuel. Therefore, the GTA is being designed for continuous duty (CW) with hydrogen as its coolant. However, the GTA will only be tested at a 2% duty factor, or less.

III. THE CRYOGENIC COOLING SYSTEM

GTA operation requires that the cryogenic cooling system: (1) cool part, or all, of the entire system to operating temperature (less than 50 K), without thermal shock to any of its components; (2) maintain the operating temperature for extended periods; and, (3) warm the components to ambient temperature at a controlled rate. The only fluids that can accommodate the requirement of operation below 50 K are neon, hydrogen, and helium.

To provide the necessary cooling to the GTA, a number of different refrigerating schemes were considered. The simplest in concept would be the direct discharge of hydrogen from a high-pressure storage Dewar at supercritical pressure through the GTA to a disposal system (flare stack). Because of the added complication and expense to accommodate the safety requirements for operation with hydrogen in the accelerator tunnel, the option of direct cooling with hydrogen was discarded.

A more sophisticated system would involve a cryogenic refrigerator that utilizes helium gas as its working fluid. However, at the refrigeration loads under consideration (50 to 250 kW), this type of refrigerator would have a much greater cost (considerably more than $10 million).

For the intermittent operation expected for an experimental facility such as the GTA (perhaps 4 hours per day, 4 days per week, for 40 weeks per year), a more economical way to obtain the required amount of cryogenic refrigeration for the GTA is to purchase liquid hydrogen from a commercial supplier, and transfer the refrigeration to the GTA by means of a transfer medium or "referee fluid." Thus, with at least two ways to obtain refrigeration and

TABLE I

GTA CRYOGENICALLY COOLED COMPONENT COLD MASS AND COOLING LOAD

Cryogenically Cooled Component	Maximum Cooling Load (kW)	Cold Mass (kg)
RFQ	1.6	680
Buncher	1.5	100
Funnel, Low energy	6.0	600
DTL	20.0	1600
Funnel, High Energy	4.0	400
DTL/CCL	150.0	1870
Steering Magnet	10.0	70

TABLE II

COOLING LOAD ESTIMATES FOR EACH GTA
EXPERIMENTAL CONFIGUATION

	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	100 MeV 100 mA	100 MeV 200 mA
Number of GTA Cryogenically Cooled Components								
RFQ	1	1	1	2	2	2	2	4
Buncher	1	1	1	0	0	0	0	0
Funnel	0	0	0	1	1	1	1	2
DTL	0	1	1	0	1	1	1	2
Funnel	0	0	0	0	0	0	1	1
Steering Magnet	0	0	1	0	0	0	1	1
Total Refr Load for GTA CCCs (kW)	4.1	24.1	34.1	10.2	30.2	34.2	194.2	223.4
Cooling Load for Other Components	2.8	8.4	11.2	4.5	10.2	11.3	57.9	66.8
Refrig Run Load, Total (kW)	6.9	32.5	45.3	14.7	40.4	45.5	252.1	290.2

several methods of supplying the refrigeration to the GTA, there are a number of possible cooling systems that could be used. Several of the refrigeration schemes that were considered are shown in Figure 4. The scheme finally chosen was No. 3 in Figure 4, with helium as the referee fluid. Actually, either helium or neon could accomplish the cooling, and the reason for the selection of helium as the referee fluid is discussed in the next section of this paper.

The cryogenic cooling system will obtain its refrigeration capability from liquid hydrogen purchased from a supplier and delivered to the GTA facility in a 50,000 liter (13,000 gallon) transport trailer. The liquid hydrogen will be stored in a 106,000 liter (28,000 gallon) storage Dewar and transferred through a 8.28 cm (3 in.) I. D. vacuum-jacketed transfer line to a smaller run Dewar. The hydrogen run Dewar will contain a helium-to-hydrogen heat exchanger to conduct the helium gas referee fluid through the pool boiling hydrogen. Additional refrigeration will be obtained from the 20 K boil-off hydrogen vapors by warming them with the returning helium gas (at 35 K) in an auxiliary heat exchanger before they are exhausted and burned in a flare stack.

The heat exchanger will be connected to vacuum jacketed cryogenic transfer lines, which lead to a circulation compressor and to the GTA. The helium circulation system will primarily consist of a 8.28 cm (3 in.) I. D. vacuum jacketed "go" line and a 9.55 cm (3.5 in.) I. D. vacuum jacketed return line. The primary cooling system will also contain a liquid nitrogen run Dewar to allow the use of liquid nitrogen for preliminary cool-down and some standby operation of the system. A heater will also be provided for rapid, but controlled warmup of the GTA. The valving and piping system will permit passage of the helium referee fluid through either: (1) the hydrogen run Dewar; (2) the nitrogen run Dewar; (3) a purifier; or (4) the warmup heater; and partially, or completely, bypass all of these items. Thus, the cryogenic system can perform all the necessary functions and the heat generated in the operation of the GTA can be absorbed by the liquid hydrogen evaporating in the run Dewar.

At the beginning of operation the system will be purged and then filled with pure helium. The GTA and referee fluid system will be filled to the operating pressure of 21 atmospheres. The helium gas will be circulated at ambient temperature through a purifier until the entire system is sufficiently

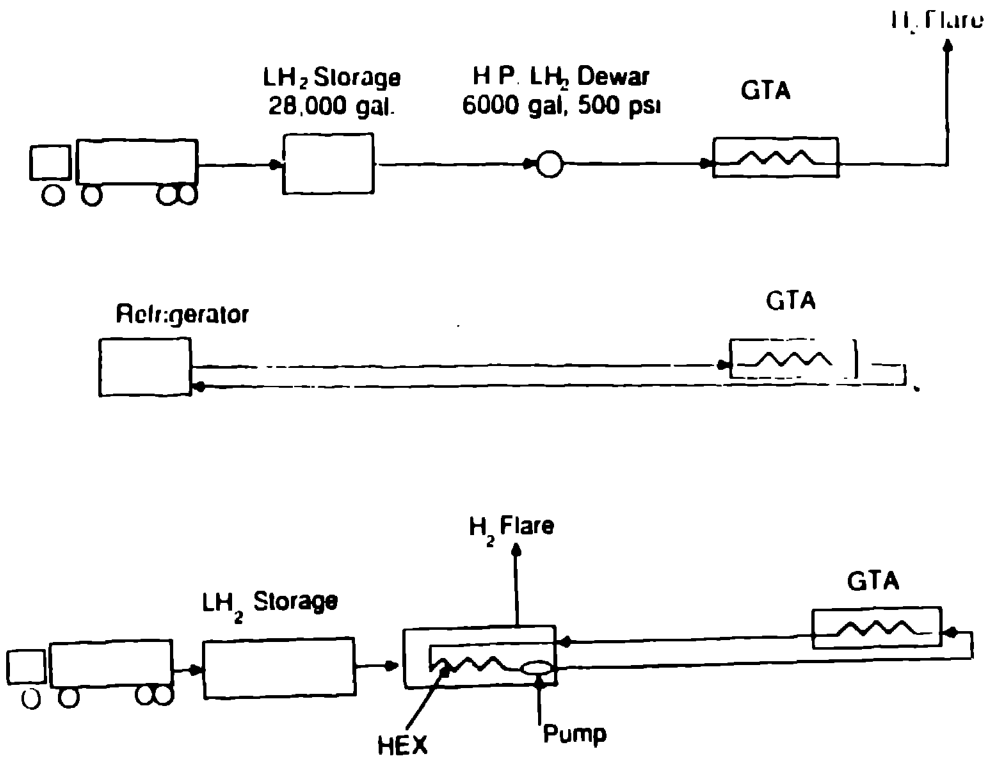

Fig. 4. Schematic diagram of three of the refrigeration methods that were considered for the GTA.

pure. During cool-down of the system helium gas will be added as needed to maintain the pressure at 21 atmospheres.

A more detailed schematic of the selected cooling system for the GTA is shown in Figure 5. This system will allow the GTA to be cooled at as slow a rate as necessary to avoid excess thermal gradients (consequently, also avoiding excess thermal stresses). This method of cool-down will be achieved by first allowing a portion of the circulating referee fluid to flow through the heat exchanger in the liquid nitrogen (LN_2) run Dewar with as large a fraction as necessary being bypassed. As the temperature of the GTA lowers, the bypass fraction can be reduced until it reaches zero. When the temperature of the GTA is close to 80 K the flow of the referee fluid can be redirected through the liquid hydrogen Dewar (again starting with some bypass flow, if necessary) to complete the cooling process.

During a short standby period, cooling can be maintained with the referee fluid flowing through the liquid hydrogen cooled heat exchanger. For longer standby periods the flow can be redirected through the LN_2 Dewar when the GTA has warmed to 75 K, and be maintained at that temperature as long as desired. Note than in all cases, the only fluid entering the GTA is the referee fluid.

During the transition from zero power to full power the fluid in the return portion of the helium circulation system will have its temperature increase from 21 K to 35 K in a period of about one minute. During this time, helium will be removed from the system to maintain a constant operating pressure. During power reductions (and consequent lowering of temperature in the return portion of the helium circulation system), helium will be added to maintain the pressure at the operating pressure level.

Because the refrigerating power needed for the first six preliminary experiments is much smaller (50 kW vs 250 kW), the cryogenic cooling system will be built in two phases, the first to accommodate a total system cooling load of 50 kW. For the larger loads of the 100 MeV experiments (last two columns in Table II) a larger cooling system will be built in a second phase.

IV. SELECTION OF THE REFEREE FLUID

As mentioned earlier, hydrogen could perform the cooling function for the GTA even better than either of the other possible fluids. However, the

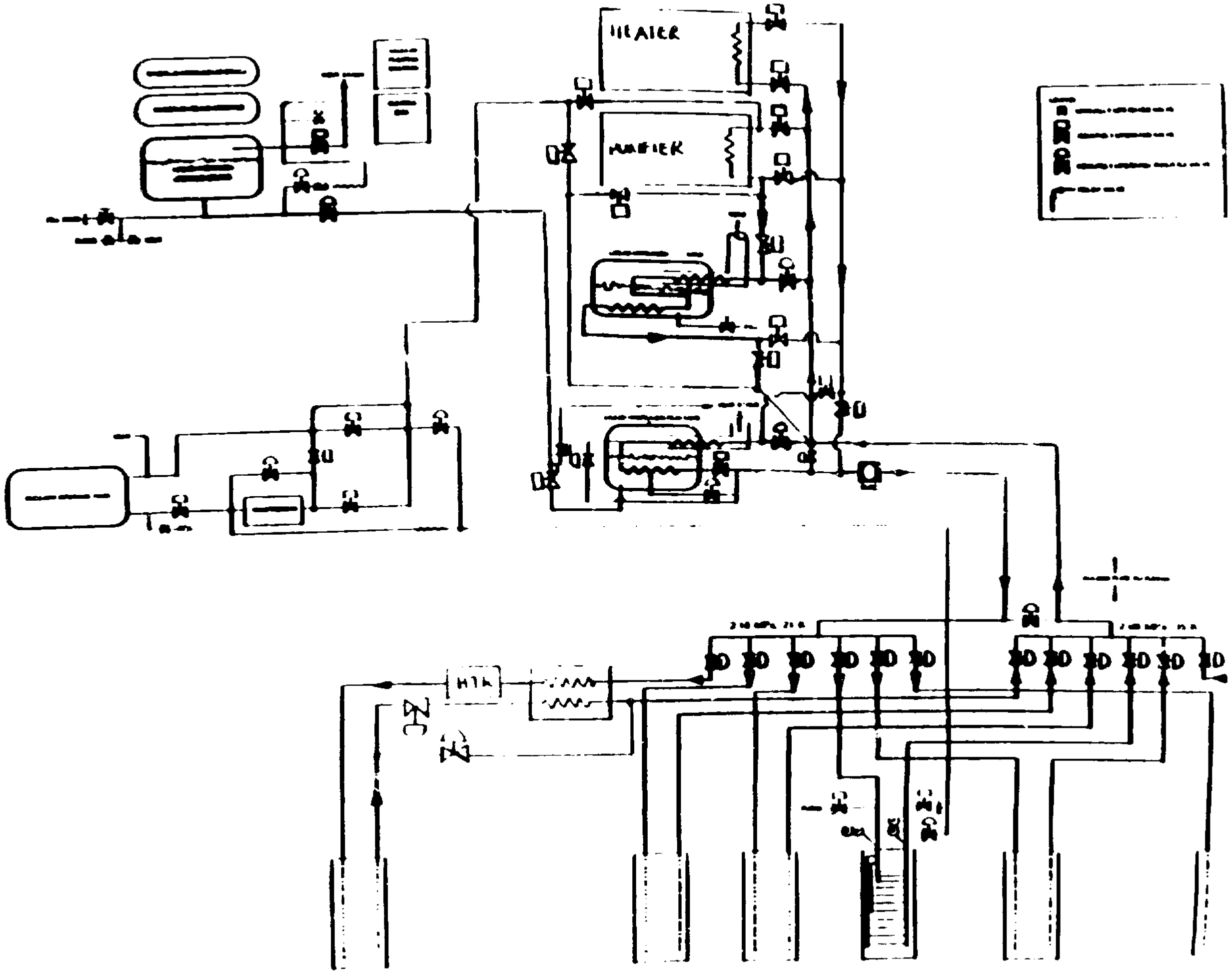

Fig. 5. Schematic diagram of the GTA cryogenic cooling system.

expense and inconvenience of the necessary safety precautions make its use unattractive. Therefore, the selection of the referee fluid can be very quickly narrowed down to two cryogens, helium and neon. Table III lists several of the pertinent properties of these two fluids, and there are several considerations involved in making the choice between them.

The most easily discussed factor is that of cost. A preliminary estimate of the cost necessary to provide the gas for one filling of the system shows a cost of $186,000 for neon vs $750 for helium.

From an operational standpoint there are several considerations that must be taken into account. A comparison of the properties of the two fluids indicates that with neon, the system operation will be very close to the two-phase dome where a slight lowering of operating pressure will allow the system to slip into the two-phase region. Therefore, pressure control becomes both more important and more difficult with neon. Also, from Table III it can be seen that to assure operation at a supercritical pressure, neon requires a minimum pressure of about 30 atmospheres, whereas helium only requires a pressure of 2.2 atmospheres (however, because the lowest temperature available is 20 K, there is no concern about two-phase flow at any pressure with helium).

Because the lowest temperature available (20 K) is far above the critical temperature for helium, there is no problem of two-phase flow or of freezing with helium operation. However, the triple point temperature of neon listed in Table III shows that neon will freeze at about 24 K. This indicates, for operation with neon, the necessity of operating the hydrogen run Dewar at an elevated pressure (about three atmospheres) to raise its temperature sufficiently to preclude freezing of the neon.

Table III also shows that neon's greater density favors a lower pressure drop when operating with neon. For this same reason, the circulating compressor becomes an easier task for neon than with helium.

Another consideration is the pressure variation during operation. With the GTA system at zero power, the entire cooling system will be filled with the referee fluid at the lowest possible operating temperature (20 K with helium, or 25 K with neon). When the accelerator is turned on, the fluid returning to the heat exchanger in the run Dewar will be at 35 K. Consequently, the quality of fluid in the system must either vary with the

TABLE III

PROPERTIES OF NEON AND HELIUM

	Neon	Helium
Physical Properties		
Critical Pressure (MPa)	2.65	0.229
Critical Temperature (K)	44.4	5.2
Normal Boiling Temperature (K)	27.1	4.2
Triple Point Pressure (MPa)	0.0433	-
Triple Point Temperature (K)	24.5	-
Molecular Weight	20.183	4.0026
System Properties at DTL (Inlet and Outlet values given)		
Pressure (MPa)	3.3-3.29	2.1-2.08
Temperature (K)	26.9-36.2	21-35
Heat Transfer Coef ($kW/m^2.K$)	4.2-5.7(27-36 K)	4.2 (21-36 K)
Density (g/cm^3)	1.231-1.052	0.049-0.027
Viscosity (MPa.s)	129-60.6	44.4-55.8
Specific Heat (J/g.K)	1.86-2.51*	6.0-5.5

*Cp values given are for saturated liquid at inlet and outlet temperatures power level, or the pressure will adjust itself to maintain constant density with part of the system (about 40%) at the higher temperature. If the latter method of operation is adopted, the neon will produce pressure variations of over 100 atmospheres, whereas helium produces about 5 atmospheres. Probably an attempt to control pressure variation will have to be made with either coolant. However, pressure control is absolutely necessary in the case of neon, and much less important in the case of helium. Finally, there is a desire on the part of the GTA designers to maintain an operating pressure no higher than 21 atmospheres, thus favoring helium over neon.

Therefore, the decision was made to utilize cold helium gas as the referee fluid for the following reasons:

1. Operating pressure can be lower with helium. Neon requires a minimum operating pressure of 27 atmospheres, whereas helium can be used at any pressure; however, the higher the pressure, the lower the pressure drop. An operating pressure of 21 atmospheres has been chosen.

2. Pressure control is easier with helium because of the smaller pressure variation between full load and no load.

3. The knowledge of physical properties (and heat transfer data) is more complete for helium.

4. The use of helium results in a cost savings of over $100,000 for each filling of the system. Although it is possible that the facility could be operated with only one filling, this would be unlikely for an extended experimental program.

5. The helium cooling system can be operated at the lowest temperature available (close to 20 K), which is an advantage to the GTA and also allows the hydrogen run Dewar to be operated at local atmospheric pressure (590 torr). With neon, the hydrogen run Dewar would have to be operated at about a three atmosphere overpressure with the additional disadvantage that thermal stratification within the run Dewar is possible and could cause some momentary local freezing of the neon.

It is recognized that there are two disadvantages to operation with helium as compared to neon:

1. The circulation compressor must be developed. Although the same statement can be made for neon, the neon is essentially a compressed liquid, and the circulating pump would be very similar to existing liquid nitrogen pumps. However, the fabrication of a helium cold compressor [illegible] felt to be readily achievable.

2. The pressure drop in the accelerator will be somewhat higher with helium than with neon. In the external circulation system the pressure drops can be made equal by selecting somewhat larger pipe sizes. The cost penalty for this is minimal. The pressure drop through the GTA will be about a factor of two higher (0.2 atm for helium vs 0.1 atm for neon). This will result in an increased cost for hydrogen refrigerant which will have a higher consumption rate because of the pump energy that must be removed. This cost is also minimal.

V. CLOSING REMARKS

Construction of the cryogenic cooling system for the GTA is scheduled to begin in January 1989, and the system is to be operational by mid 1990. With one exception this cooling system utilizes only standard, well-developed components. That exception is the compressor to effect the circulation of the referee fluid, which requires the development of a cold compressor or pump. This would probably be less of a development with the utilization of neon as the referee fluid than with the helium. In either case, the fluid will have to be kept above its critical pressure to avoid two-phase flow with the consequent higher pressure drop and the liklihood of pressure and flow oscillation. However, the belief that this is not an insoluble problem is supported by at least three manufacturers with experience with smaller cold compressors or pumps.

As soon as some operating experience is gained with the first phase, design of the second (larger) phase of the system will begin.